Insight into the 2005 hydrothermal eruption at South Orakonui, Ngatamariki Geothermal Field, New Zealand from calcite microthermometry

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ABSTRACT

On the 19th April 2005, a small hydrothermal eruption took place at South Orakonui, Ngatamariki Geothermal Field. Prior to the eruption there were significant changes in the surface thermal features with the appearance and demise of some springs that discharge mixed chloride-bicarbonate waters with temperatures up to 88ºC. The 2005 eruption occurred at the southern edge of the largest pool and ejected material mostly towards the east, creating a debris blanket covering ~70 x 60 m and 0.3 to 4 m thick. Amongst the mud and rocks ejected are vein fragments of platy calcite; the largest vein fragment measures 19 x 17 x 5 cm and has five bands of bladed calcite. Rarely the veins fragments have attached selvages of the host rock which is sediments of the Huka Falls Formation. Measured fluid inclusions in two samples of platy calcite have narrow homogenisation temperature ranges of 131º to 133º (median 132ºC) and 141º to 157ºC (median 143ºC) with dilute apparent salinities. Under hydrostatic conditions these platy calcite veins formed at 20 and 32 m depth below the water table and provide minimum source depths of ejected material. Sealing of these veins that are hosted in generally impermeable Huka Falls Formation sediments likely resulted in pressure build-up and caused the hydrothermal eruption.

1. INTRODUCTION

The Ngatamariki Geothermal Field is located within the Taupo Volcanic Zone (TVZ) approximately 20 km north-west of Taupo. Its surface expression is represented by few surface thermal manifestations with low discharge hot springs discharging from two main areas along the Orakonui stream (North Orakonui and South Orakonui) located 1.0 and 1.8 km from the confluence with the Waikato River (Fig. 1). There are also smaller hot springs present on the banks of the Waikato River and minor seeps at the centre of the field (O'Brien et al., 2011). A number of hydrothermal eruptions have occurred at Ngatamariki as evidenced from their surficial eruption deposits and craters (Brotheridge et al., 1995) with the most recent eruption occurring on the 19th of April 2005 at South Orakonui. In this paper we describe changes in the thermal features since 1948 at South Orakonui and the 2005 hydrothermal eruption. We also detail fluid inclusion microthermometry results for platy calcite vein clasts that have been used to calculate the source depth of this erupted material.

2. GEOLOGY

The surface geology at Ngatamariki consists of Taupo Pumice Alluvium, Oruanui Formation, Huka Falls Formation and the Whakapapataringa rhyolite (Leonard, 2010; Chambefort et al., 2014). Both the North and South Orakonui thermal features are located in valleys filled by Taupo pumice alluvium, derived from the 232 AD Taupo volcanic eruption (Leonard, 2010). The alluvium overlies unconsolidated ignimbrite and pumice breccias of the Oruanui Formation, which crop out east and west of the springs. Below this are lacustrine interlayered mudstone and siltstone of the Huka Falls Formation (Leonard, 2010; Chambefort et al., 2014). In places, the lacustrine sediments are clay-rich and are thought to restrict vertical flow of deep-sourced thermal fluids. The Whakapapataringa rhyolite dome to the west of the Orakonui springs is surrounded by lithic and pumiceous breccias formed during dome emplacement. Recent pyroclastic and alluvial deposits obscure structures, although north-northeast trending lineaments that correlate with stream courses and topographic features are visible on aerial photographs (Brotheridge, 1995).

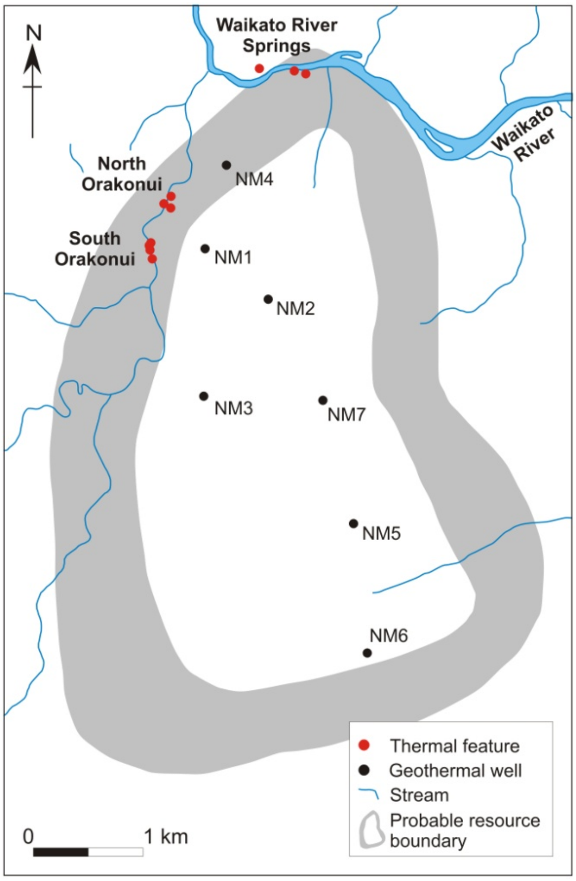

Figure 1: Ngatamariki Geothermal Field showing the location of thermal features and the probable resource boundary (after O'Brien et al., 2011).

3. SOUTH ORAKONUI

The South Orakonui thermal area has three main pools (Fig. 2). Over the past 65 years there have been significant changes in the surface expression of thermal manifestations at South Orakonui with two documented hydrothermal eruptions in addition to the appearance and demise of some springs and associated pools.

The South 1 pool is the largest naturally discharging thermal feature at Ngatamariki. It occupies a crater created by a hydrothermal eruption in 1948 and is also the site of the 2005 hydrothermal eruption. Presently the pool measures 28 x 44 m and discharges mixed dilute chloride-bicarbonate water into the Orakonui stream. It is fed by at least five springs along the pool edges with temperatures of 41º to 88ºC. In 1995, the South 1 pool was 2.85 m deep and of near identical dimension (Brotheridge, 1995; Brotheridge et al., 1995), but in 1998 was dry with only small, weakly discharging springs on the former pool margins (Campbell et al., 2002).

Three other pools close to South 1 are South 2, 3 and 4 (Fig. 2). South 2 occurs 50 m south of South 1 and is 12 x 6 m across. It has an average temperature of 74ºC that has remained essentially unchanged since 1994. South 3 is located ~30 m north of South 1. In 1981, the pool was 23 m across and 8 m deep. It has adjacent breccia deposits of unknown provenance but may be sourced from an eruption crater now occupied by the pool (Brotheridge et al., 1995). In 1981 the pool discharged 81ºC water with minor silica precipitation, but by 1994 the water level had dropped 1.5 m, the temperature declined (79ºC) and surface outflow had ceased (Brotheridge, 1995). The pool has receded further and presently has an average temperature of 28ºC. South 4, also known as Pavlova spring, is located 40 m northeast of South 3. It discharged fluids from 1993 to 2003, with its inception reportedly coinciding with a fall in the water level of South 3 (Campbell et al., 2002). Pavlova spring when active, discharged vigorously bubbling fluids at 88ºC from a single vent, outflowing into the Orakonui stream along a 11.5 m channel that was locally up to 4 m wide. Both the spring and channel are rimmed by an atypical sinter composed of silica (opal-A) and minor calcite (Campbell et al., 2002; Mountain et al., 2003).

4. HYDROTHERMAL ERUPTION

At 10.30 am on April 19th 2005, a hydrothermal eruption occurred at the southern end of the then dry South 1 pool (Fig. 2). The major part of the eruption lasted about 2 hours with rock and steam ejected up to 200 m vertically (Venzke, 2005). Both steam and water continued to jet up to a height of approximately10 m for up to 5 hours post-eruption. Most debris ejected from the main crater was directed towards the east, being restricted to the west by a ~50 m high cliff. The eruption flattened and buried the surrounding 2 m high blackberry bushes and damaged or toppled numerous adjacent pine trees (Fig. 3a). The debris blanket (Fig. 3b) was ~70 x 60 m across and varied in thickness from 0.3 m to locally 4 m, with an estimated volume of 7,000 to 10,000 m^3 (Venzke, 2005). The eruption breccia temporarily blocked the Orakonui stream for ~4 hours before it breached and discharged muddy waters into the Waikato River. Following the eruption, intense steam venting occurred within the eruption crater with muddy boiling water (98ºC) filling the adjacent main pool that was separated by a thin dam. However, the steam venting ceased a day after the eruption due to the vent also becoming filled by hot water (Fig. 3).

The 2005 eruption deposit is a poorly-sorted, matrix-supported polymictic breccia (Fig. 3e), composed predominately of mud and subrounded to rarely subangular rock clasts. Most rock clasts are 0.5 to 5 cm in length, with sizes decreasing away from the vent. Within 10 m of the vent rare clasts are up to 73 cm in length (Fig. 3c), and 80 m from the vent the maximum size is 15 cm in length. Lithic clasts mainly consist of pumice derived from both, the Taupo Pumice Alluvium and the Oruanui Formation as well as mudstone and siltstone of the Huka Falls Formation. Also present are vein fragments of platy calcite.

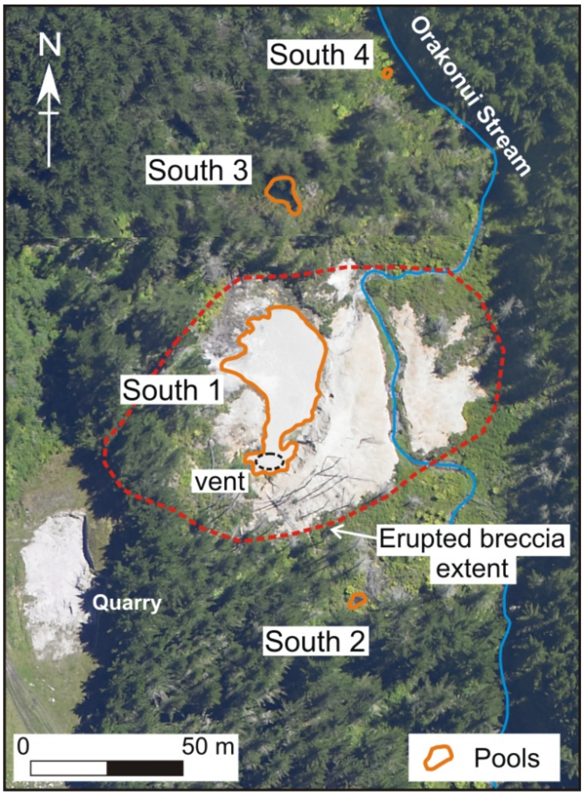

Figure 2: Aerial image taken in 2009 showing thermal features of South Orakonui (modified Milicich and Reeves, 2009). Red dashed line broadly defines the distribution of erupted material.

An indication of explosivity of the 2005 eruption can be assessed, at least to a first order, by reconstructing ballistic trajectories for a range of ejected fragment sizes. We ran iterations of the *Eject!* model of Mastin (2001) to derive velocity parameters that closely replicate the measured dispersal of 5 cm, 15 cm, and 70 cm sized lithic blocks. Initial particle velocity is an important control on the extent of particle dispersion and we take modelled values of this parameter and the radial extent of debris as a relative measure of explosivity. Values of parameters used in *Eject!* modelling were: coefficient of drag 0.7, block shape approximated by a cube, diameter (5, 15, 70 cm), density 2000kg/m^3, tailwind 0 m/s, no drag zone around vent, landing point elevation = vent, ejection angle 45^o, distance of landing point (65, 80, 10 m). Initial velocities derived from the model to replicate actual distances for each block were 31 m/s (5 cm), 30 m/s (15 cm) and 10 m/s (70 cm). By comparison with the well documented 1981 eruption at Tauhara Geothermal Field (Scott & Cody, 1982; Browne & Lawless, 2001), the South Orakonui eruption ejected a

Figure 3: Images of the South Orakonui eruption crater and breccia. A) Steaming crater rimmed by raised apron of breccia that also blankets the surrounding area. The erupted debris has damaged and also toppled adjacent pine trees. B) Northeastern portion of the breccia blanket comprised of mud and small rock clasts. This temporally dammed the Orakonui stream. C) A large ejected breccia clast (images A, B, & C taken ~4 hrs after the eruption). D) The eruption crater as seen 27th April, filled by muddy thermal waters. E) Poorly sorted, matrix-supported, polymictic breccia with subrounded pumice and sediment (Huka Falls Formation) clasts as seen exposed in the inner crater rim, 2014.

similar area, maximum thickness, and volume of debris (17 x 10^3 m^2, 2 m and 6.8 x 10^3 m^3 at Tauhara; 15-30 x 10^3 m^2, 4 m and 7-10 x 10^3 m^3 at South Orakonui) but was approximately an order of magnitude less violent. Minimum derived ejection velocities for Tauhara 1981 are 100 m/s compared with 10-30 m/s for South Orakonui.

5. PLATY CALCITE VEIN FRAGMENTS

Included within the breccia are remarkably intact vein fragments of platy calcite and these vein fragments are the largest discovered to date within a hydrothermal eruption deposit of the TVZ. These clasts comprise <1 percent of erupted material, but there are many examples, and the largest measured 19 x 17 x 5 cm (Fig. 4). Most calcite vein clasts have no obvious attached selvages of host rock, although some have surface indentations indicative of the vein margin. Rare fragments have thin selvages of mudstone indicating that the veins are hosted within sediments of the Huka Falls Formation. The veins range from <2 to >5 cm in width. Some have only a single band of platy calcite, but multiple bands (i.e., 2 to 5) are more common, with individual bands being 7 to 14 mm in width. Calcite has skeletal intergrowths of semi-translucent to opaque milky white individual blades that are 1 to 15 mm in length and <0.1 mm thick. Many of the vein fragments have 40 to 70 percent open spaces between blades, although some have denser intergrowths with <20 percent open spaces and these can have thicker plates (0.5 to 1.0 mm wide). In the largest vein fragment with multiple bands, there are voids within the bands, but there are also lensoidal partings (<0.5 – 5 mm wide) between bands filled by grey mud. From XRD analyses this mud is comprised of smectite, quartz and trace pyrite, with no calcite detected.

The diversity of vein fragments showing single and multiple banding, coupled with some that appear sealed and others that have crystals grown into open spaces, suggest that these are fragments from multiple veins, and possibly sourced from a range of depths.

6. FLUID INCLUSION MICROTHERMOMETRY

Polished fluid inclusion wafers were prepared from individual calcite crystals extracted from seven different vein fragments. Microthermometry measurements were made to determine the temperature and apparent composition of the trapped fluids in the inclusions (c.f. Bodnar et al., 1985).

Unfortunately, the fluid inclusion wafers for the common thinner platy calcite crystals (<0.1 mm) are typically semi-opaque to semi-translucent and the contained fluid inclusions are by and large not clearly visible and able to be measured. The inclusions that could be measured occur in two different vein fragments (samples A and B) that have less common, but thicker (<1 mm) and translucent calcite blades. In both samples only two-phase liquid-rich fluid inclusions are observed and these contain 7 to 8 volume percent vapour. In sample A, the liquid-rich inclusions have irregular to regular shapes that are on average 20 µm in length and occur along distinct parallel aligned trails. These inclusion-rich trails appear to have developed perpendicular to the calcite crystallographic c-axis, and are suspected to be of primary origin (c.f. Simmons and Christenson, 1994). In contrast, the platy calcite of sample B is crowded by abundant fluid inclusions. They range in size from 5 to 110 µm (average 25 µm), lie coplanar with their host crystal, and are also interpreted to be of primary origin (c.f. Simmons and Christenson, 1994).

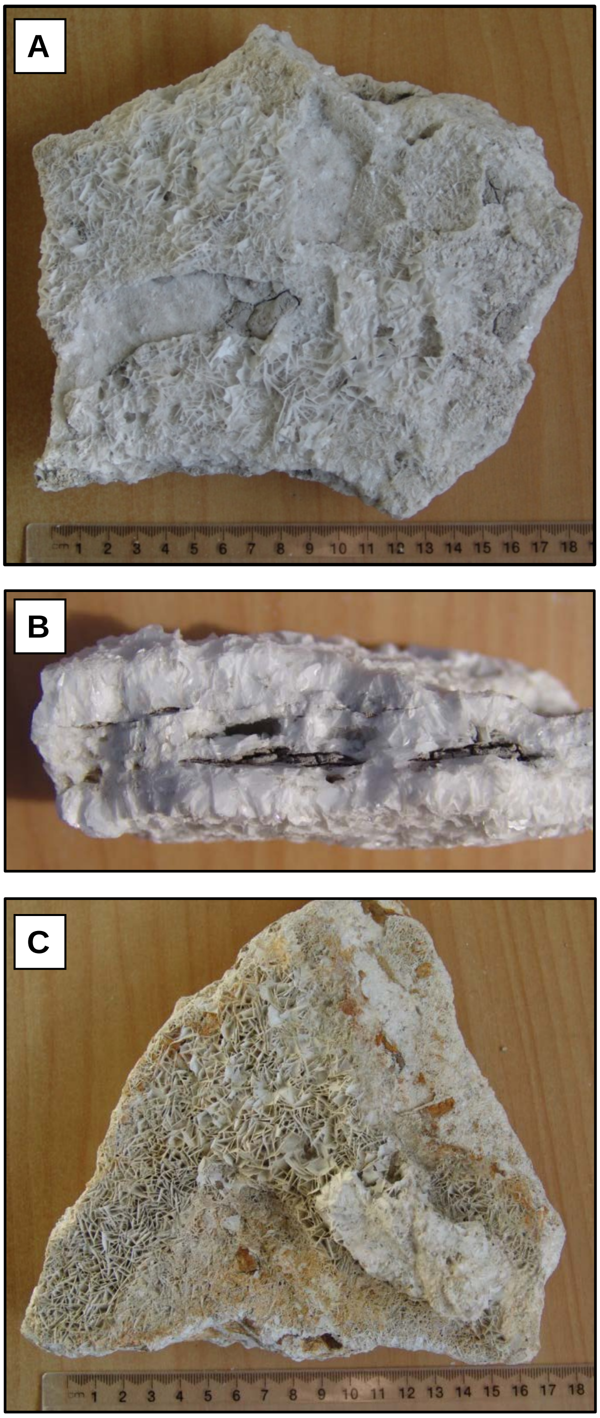

Figure 4: Images of platy calcite vein clasts from the eruption breccia. A) Large platy calcite vein clast with side view (B) showing multiple bands of platy calcite separated by thin lenses filled with clay. C) Another large vein clast of platy calcite.

Fluid inclusion microthermometric measurements were made using a Linkam THMSG600 heating and cooling stage with apparent salinity calculated from the final ice melting temperature (T_m) using the equation of Bodnar (1993). Heating-freezing measurements were made on fluid inclusion assemblages carefully differentiated prior to analysis. Each assemblage is a group of inclusions that are assumed to have been trapped simultaneously in a single event, such as an individual growth zone or a healed fracture (Goldstein and Reynolds, 1994).

Homogenisation temperatures (T_h) for fluid inclusions in sample A, despite occurring in several parallel trails, have a narrow range of 131º to 133ºC (n=23; Fig. 5). Only limited T_m measurements were obtained due to the vapour bubble in most inclusions disappearing on freezing and no ice discernible; although on heating the vapour bubble reappeared at ~5ºC. The T_m values range from 0.0 to -0.1ºC (n=3) and correspond to an apparent salinity of less than 0.2 weight percent NaCl equivalent (Bodnar, 1993). Slightly hotter T_h values were determined for inclusions in sample B, ranging from 142º to 157ºC (n=20; Fig. 5); although most homogenised between 142º and 145ºC (n=18). On freezing the vapour bubbles similarly disappeared for most inclusions. Only two T_m values were obtained, -0.3º and -0.6ºC, corresponding to an apparent salinity of less than 1.1 weight percent NaCl equivalent (Bodnar, 1993).

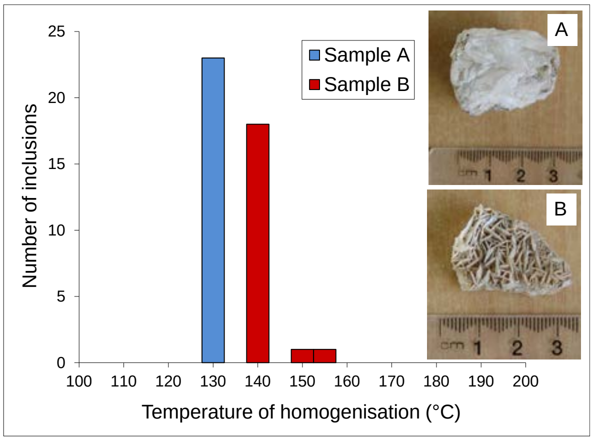

Figure 5: Fluid inclusion T_h results for two vein fragments of platy calcite. Insets are images of the two fragments from which plates were extracted and analysed.

7. DISCUSSION

Breccia ejected during the 2005 hydrothermal eruption from South 1 remarkably include vein fragments of platy calcite that are up to up to 19 cm in length and 5 cm wide. The distinct platy morphology of the calcite crystals indicates formation from geothermal fluids during boiling (Tulloch, 1982; Simmons and Christenson, 1994). Furthermore, the occurrence of platy vein clasts with either single bands or more commonly multiple bands of bladed calcite is consistent with their formation in several different veins, and possibly a stockwork.

Fluid inclusions in individual calcite plates have narrow T_h ranges with medians of 132º and 143ºC, with apparent dilute salinities. These temperatures overlap with that inferred from rare included smectite lenses that locally occur between bands of platy calcite with this clay typically stable at <150ºC (Steiner, 1968). The minimum formation depth of these veins below the piezometric surface can be estimated from the trapping temperature of fluid inclusions. Since the inclusions are primary and hosted in platy calcite they are interpreted to have been trapped under boiling conditions (c.f. Simmons and Christenson, 1994), even though no co-existing vapour-rich inclusions were seen. Thus the homogenisation temperature can be considered equivalent to the trapping temperature and no pressure correction is required (c.f. Bodnar et al., 1985). Assuming hydrostatic conditions, fluid inclusions in platy calcite sample A, with a median T_h of 132ºC, would have formed at a depth of 20 m below the piezometric surface and at pressure of 2.9 bars (Haas, 1971). Whereas, inclusions in platy calcite sample B, with a median T_h of 143 ºC, would have formed at a depth of 32 m and 4.0 bars pressure. These calculations suggest that these two platy calcite vein fragments have formed at different depths and some of the ejected material has been sourced from as deep as 32 m below the piezometric surface.

Hydrothermal eruptions are common in many liquid-dominated geothermal systems. Recent eruptions (past 150 years) in the TVZ have a maximum estimated focal depth of 90 m (e.g. Rotorua and Wairakei), whereas extensive prehistoric breccia deposit show there have been much larger eruptions with estimated maximum focal depths of 190 – 450 m (i.e. Kawerau, Waiotapu, Rotokawa) (Browne and Lawless, 2001). Hydrothermal eruptions can occur in areas where the vapour pressure (steam ± gas) of the geothermal fluid increases due to an impermeable barrier (‘caprock’) and exceeds the hydrostatic pressure for a given temperature. This caprock commonly can form due to hydrothermal alteration and / or mineral precipitation that reduce permeability. Triggers for the breach of the caprock include; lowering of the piezometric surface, seismically induced subsurface fracturing, removal of overburden (rock or water in the form of a lake), chemical dissolution, and in the case of larger eruptions the addition of heat due to magmatic input (Browne and Lawless, 2001). Browne and Lawless (2001), suggest that the most common cause of hydrothermal eruptions in geothermal fields is due to progressive flashing: the ‘top-down’ model. This requires that boiling water exists at, or close to, the surface and this is underlain by water at a boiling point for depth temperature gradient. A drop in confining pressure results in the rapid formation of steam at ground surface and an initial steam burst brecciates, lifts and ejects cover material thereby further reducing pressure, resulting in the influx of boiling fluid and a descending flashing and brecciation front. This continues downwards until the rate and volume of steam produced is insufficient to brecciate, lift, and displace the rock.

At South Orakonui, we propose the sealing of veins resulted in the 2005 hydrothermal eruption. It is inferred that the permeability structure is controlled in part by the host rock and by fractures. Permeability for the overlying pumice formations is presumably rock controlled, due to the high intrinsic porosity of the pumice. In contrast, the permeability of the underlying Huka Falls Formation that hosts the calcite veins is fracture and rock controlled. The clay-rich sediments of the Huka Falls Formation have low permeability and is interpreted in other parts of the Ngatamariki Geothermal Field to act as a barrier to vertical flow of deep-sourced thermal fluids (Boseley et al., 2010). From 1998, South 1 pool, the site of the hydrothermal eruption became almost dry with only small springs reflecting restricted surface discharge and possibly slight lowering of the piezometric surface. Additionally, the demise of South 3 pool (reduced temperature and ceased outflow by 1994), coupled with the appearance and demise of South 4 pool (1993 – 2003) indicate a reduction in vertically connected fluid flow in these areas likely due to self-sealing via precipitation of calcite in fluid conduits and pore spaces. It is proposed that the sealing of platy calcite veins in generally impermeable sediments below South 1 blocked the ascent of boiling fluids resulting in steam and gas build-up and the hydrothermal eruption. Calcite precipitation can take place very quickly; for example platy calcite scale deposited in wells of the Ohaaki geothermal field is estimated to have grown 0.1 mm per day (Tulloch, 1982). Based on this growth rate, the multiple bands that form the 5 cm wide platy calcite veins from Ngatamariki could have formed in as little as 1.4 years. The poorly consolidated nature of the overlying rocks probably absorbed much of the energy released during the hydrothermal eruption and thereby limited the depth of eruption excavation (c.f. Browne and Lawless, 2001).

8. SUMMARY

Numerous natural changes in thermal manifestations at South Orakonui have occurred during the last 65 years, including two hydrothermal eruptions in 1948 and 2005. These changes highlight the naturally transient behaviour of near surface thermal activity. In 2005 the small hydrothermal eruption from South 1 ejected vein clasts of platy calcite. The sealing of fluid conduits by calcite precipitating via boiling was likely instrumental in the cause of over-pressuring and the 2005 hydrothermal eruption.

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